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Analysis

Environmental Impact of Consumption by Czech Households: Hybrid Input–Output Analysis Linked to Household Consumption Data

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ABSTRACT

We quantify direct and indirect emissions resulting from Czech household consumption contributing to climate change, acidification and smog formation. We develop a hybrid environmentally extended input–output model that links the single-region input–output analysis on domestic processes with a multiregional input–output analysis to derive the indirect emissions associated with imports and part of the domestic production. We apply Almon's algorithm to transform the domestic emissions from industries to product groups. The indirect and direct emission intensities of more than hundred consumption items are then linked to expenditures of almost 3000 individual households to compute the total emissions for each household.

We find that emissions attributable to households are not distributed evenly — while the first expenditure decile of households is responsible for less than 4% of all emissions, the tenth decile is responsible for 20–24%. Consumption of services and goods is least emission intensive, while use of electricity, heating, and transportation remains responsible for the major part of emissions. The most important factor of emissions attributable to household consumption is total expenditures; the expenditure elasticity of emissions is about 0.8, but we identify consumption groups which emissions are less sensitive to total expenditures (electricity, heating and food) and more sensitive (transportation, goods).

1. Introduction

The environmental burden from air pollution and greenhouse gases (GHG) causes substantial economic costs and considerable adverse health and non-health impacts (OECD, 2014; WHO and OECD, 2015).[1] Household consumption is responsible for two thirds of GHG emissions worldwide (Hertwich and Peters, 2009; Ivanova et al., 2015).

While application of the environmentally extended input–output analysis (EE-IOA) to derive emissions attributable to household demand is not new (see Andrew et al., 2009; Herendeen and Tanaka, 1976; Suh, 2009), only a few studies exist that have computed the total emissions for individual households, or for several different household categories by linking environmental extensions, input–output tables and individual expenditure data. Among these few studies, several papers have focused on emissions attributable to households with different incomes or expenditures (Druckman and Jackson, 2008; Golley and Meng, 2012; Kerkhof et al., 2009b; Steen-Olsen et al., 2016; Weber and Matthews, 2008), or households that differ with respect to other household characteristics (Baiocchi et al., 2010; Lenzen et al., 2004; Peters and Hertwich, 2006). Some papers have aimed primarily at making comparisons of household emissions across countries (Kerkhof et al., 2009a; Peters and Hertwich, 2006). A comprehensive overview of studies dealing with household emissions for different countries has been made by several authors (Di Donato et al., 2015; Hertwich, 2005; Tukker et al., 2010, 2006).

The single-region environmentally extended input–output analysis (SR EE-IOA) may lead to over- or underestimation of emissions related to imported products due to the domestic technology assumption (Weinzettel and Kovanda, 2009). In order to incorporate differences in production technologies between countries, the multiregional environmentally extended input–output analysis (MR EE-IOA) has come into practice in the last decade. A downside of the currently available global multiregional input–output datasets is the lack of the desired level of detail (Steen-Olsen et al., 2014) or quality issues in comparison to the single-region input–output table (Schoer et al., 2013).

The main contribution of this paper to the recent literature is

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[1] The World Health Organisation and OECD (2015) quantified the annual economic cost of the health impact of air pollution in Europe at US$ 1.575 trillion: that is equivalent to more than 1% of the gross domestic product of the region. Emissions of air quality pollutants also cause other non-health problems, including impacts on agriculture crops, building materials, and ecosystems; however, the health impacts contribute more than 90% of the total value of damage (Maca et al., 2012; Ščasný et al., 2015).

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achieved by linking several databases in order to derive the total emissions for individual Czech households and hence to provide a better picture of households' responsibility for their environmental burden. For that purpose, we have developed a hybrid input–output method that links a global environmentally extended multi-regional input–output table, based on EXIOBASE 2 database, with a domestic single-region input–output table (IOT) and domestic emissions data from NAMEA,[2] both for the Czech Republic. We then link input–output results to household consumption data from the consumer expenditure survey (CES) of Czech households. Using this method, we quantify the total indirect emissions for several hundreds of consumed items for each of the nearly 3000 Czech households surveyed, and add them to direct emissions stemming from household fuel combustion. To ease the interpretation of our results, we present the average values and values related to expenditure deciles to present variability between different expenditure levels. Further, we use expenditure elasticities similarly as in several other studies (Golley and Meng, 2012; Kerkhof et al., 2009b; Weber and Matthews, 2008), to depict the dependency of emissions on the total expenditures.

In order to deliver results that better reflect the reality, we have included several additional enhancements compared to common practices. Special effort was devoted to electricity and heat in this regard. In order to obtain accurate values of local emissions from industries, we compile more detailed NAMEA, disaggregate its electricity to electricity from fossil fuels and other electricity, apply Almon's algorithm (Almon, 2000) to avoid negatives in transformation of NAMEA from industries to products and keep the product technology assumption at the same time, and apply the transformation method close to the industry technology assumption for the joint production of electricity from fossil fuels and heat.

An additional added value of our study is the calculation of eleven pollutants induced by household consumption for a country in Central and Eastern Europe, as such an analysis has not yet been performed for this region in such detail.

2. Methodology

Total emissions attributable to the consumption of each household are quantified in our study for eleven different pollutants overall, which are merged into three different environmental impact categories[3]: greenhouse gases that contribute to climate change (including CO_2, CH_4, N_2O, HFCs, PFCs, SF_6), pollutants causing acidification (SO_2, NH_3, NO_X), and precursors of photochemical smog formation (NMVOC, CO).

Direct emissions come from fuels burnt by households to heat their dwellings and to propel their vehicles, whereas indirect emissions stem from industries, agriculture and transportation of goods, including both domestic production and imports. The total emissions are the sum of direct and indirect emissions and are quantified separately using two different calculation processes.

2.1. Direct Emissions

In principle, direct emissions result from fuels burnt by households. In our study, direct emissions are calculated for eight different fuels in total (natural gas, lignite, bituminous coal, coke, fuel wood, gasoline, diesel fuel and LPG), which cover the vast majority of the fuel consumption of Czech households (see Supporting information for particular values). We determine direct emissions from household expenditures (CZSO, 2011a), fuel prices (CZSO, 2014; ERU, 2009; MPO, 2012), emission intensity (Adamec et al., 2005; EEA, 2007; MZP, 2009), and physical properties, such as density (Beranovský and Truxa, 2004; ČEPRO, 2011a, 2011b), calorific value (Beranovský and Truxa, 2004) and sulfur content (Top palivo-teplo, 2015). All direct emissions of NH_3, HFCs, PFCs, and SF_6 as well as emissions of N_2O for natural gas are regarded as negligible.

2.2. Indirect Emissions

We quantify indirect emissions by combining the EE-IOA with household expenditures (Herendeen and Tanaka, 1976). This method virtually re-allocates the emissions from industries to final demand products and it quantifies emissions related to the complete production chain of each product purchased by each household.

In order to cover the full global production chain including imports and their upstream emissions, we combine two input–output datasets. First, the global multiregional environmentally extended input–output database (MR EE-IOT) EXIOBASE 2 (Wood et al., 2015), that describes the financial flows within the global economic system, is applied to estimate the upstream emissions of products imported to the Czech intermediate economy consumption and final demand. Second, we use the domestic single-region CZ-IOT,[4] which describes the financial flows among all product groups within the studied region (country).

We apply this hybrid input–output method because we consider that using the single-region CZ-IOT is more accurate as it describes the economy for the same year in which the CES records the household expenditures, and because using the global MR EE-IOT is a more accurate way to characterize imports than to follow the domestic technology assumption if the CZ-IOT was used. A similar hybrid method was applied earlier by Schoer et al. (2012) and Weinzettel and Kovanda (2009) for selected products.

In order to assure mutual compatibility between different databases used within this paper, several transformations and disaggregations need to be carried out in parallel to the input–output analysis itself. As a general rule, all manipulations are carried out in such a manner as to retain the utmost detail of available information, since it has been shown that a high level of detail can significantly improve the accuracy of the results (Steen-Olsen et al., 2014).

To obtain the resulting indirect emissions for each household, we derive embodied emission intensities of product groups[5] (steps 1 to 5), link them with household expenditures (steps 6 to 9) and calculate individual emissions of eleven pollutants (step 10). Then we add the direct emissions, convert the total emissions to environmental impact categories and group them into six consumption groups (Section 2.3). We carry out this procedure in sequential steps described in the following sections:

1. Disaggregation of nationally recorded emissions to match CZ-IOT

Emissions of domestic industries for 2010 recorded in CZ-NAMEA for 88 industries of NACE rev. 2 classification (CHMI, 2012) are disaggregated into 184 industries (see Supporting information 1 for particular values) of the resolution[6] of 2010 CZ-IOT. For major sources of emissions (larger than 0.2 MW of heat power), we sum emissions of individual enterprises based on the first three digits of their NACE codes (CHMI, 2014). For separately recorded minor stationary and mobile emission sources, where emissions are not assigned to enterprises with NACE codes, emissions are adopted from CZ-NAMEA and subdivided in the ratios of fuel consumption in each industry. This ratio is acquired from the detailed domestic use table of 2010 (CZSO, 2012). Coal and

[2] NAMEA stands for National Accounting Matrix with Environmental Accounts.

[3] The impact categories, see i.e. Kerkhof et al. (2009b), do not translate the impact to damage, as for example, in Weinzettel et al. (2012)

[4] In order to ease the clarity of our method, we denote country specific databases by the prefix CZ further in the text, as our study site is the Czech Republic. Yet this approach can be applied to any country or region for which such data is available. The selection of the year 2010 is determined by data availability: for instance, the detailed version of the CES is available for 1999 and 2010 and EXIOBASE 2 is available for 2000 and 2007 only.

[5] The term product and product group may be used interchangeably.

[6] Resolution stands for a size of the matrix or vector describing the system.

natural gas, weighted by their direct emission intensities, are used to represent stationary sources and oil products solely are used to represent mobile sources.

Greenhouse gases from non-combustion processes are primarily based on the Czech National Inventory Report (NIR) (CHMI, 2016). Where CZ-NIR does not provide enough detail, records from CZ-NAMEA, disaggregated by the ratios of total used resources of CZ-IOT are utilized. The emissions from CZ-NIR are added after the transformation from industries to product, because CZ-NIR collects data on emissions of products.

2. Transformation of the disaggregated emissions from industries to products using Almon's algorithm

We carry out the transformation of emissions from industries to products, because industries produce both a main product and by-products. Since by-products are prevailingly an outcome of the separable subsidiary production in the Czech supply table, the product technology assumption is the most suitable method here. To eliminate the resulting negatives, we use Almon's algorithm (Almon, 2000; Eurostat, 2008). A comparison of Almon's method and standard model A method with manual negative removal can be found e.g. in Vollebregt and van Dalen (2002).

Solely for the purpose of Almon's algorithm, the electricity sector was split into electricity from fossil fuels and electricity others. Additionally, electricity from fossil fuels and heat form the most important joint products with regard to emissions. For that reason, these two sectors are merged for processing with Almon's procedure, then disaggregated using their original ratio. Finally, they are transformed to products using the transformation method close to industry technology assumption (model B) based on the respective sections of CZ-IOT. While the original Almon's algorithm transforms rows of the use table, we transform 11 emissions instead (see Supporting information 2 for particular values). We use a VBA script that we developed. For more details on disaggregation and its effect on transformation, and for the VBA script used, see Mach et al. (2017).

3. Hybrid input–output method for domestic and imported products

First, the upstream emissions of imports to the Czech Republic, $\boldsymbol{F_{imp}}$,[7] are calculated through an environmentally extended multi-regional input–output analysis for 2007 (the reference year for EXIOBASE 2) by substituting the final demand vector with a vector representing the total imports to the Czech economy and utilizing the multiregional emission intensity and technical coefficient matrices, $\boldsymbol{D_{MR}}$ and $\boldsymbol{A_{MR}}$ respectively, from EXIOBASE 2. The multiregional diagonalized vector of total imports is comprised of imported products into intermediate consumption and final demand. It is specific to the region of origin of the imported products in the multiregional IO framework.

$$\boldsymbol{F_{impreg}} = \boldsymbol{D_{MR}}(\boldsymbol{I} - \boldsymbol{A_{MR}})^{-1}\widehat{m}_{MR} \tag{1}$$

$\boldsymbol{F_{impreg}}$ contains information regarding the origin of the imported product, which cannot be utilized for further steps and the regional resolution of this vector is therefore aggregated in order to keep the product detail only, resulting in a matrix $\boldsymbol{F_{imp}}$.

The second step is to convert the emissions induced by Czech imports, $\boldsymbol{F_{imp}}$, to the resolution of the domestic IOT. The emissions are summed where industries of the multiregional database are more detailed, and divided in the ratio of imports where the domestic database offers greater detail. Since the multiregional and domestic IOTs are from different years, deflators of imports are utilized to remove the effects of inflation, and the ratio of imports between the different years from the domestic IOT is used to reflect differing import volumes.

The results of this procedure are upstream emissions of all imported products from the whole production chain.

In the next stage we identified imported products with better product detail within the domestic single-region input–output table and with differences in emission intensities higher than 20%. For those imported products we assume that the domestic technology assumption (DTA) gives more accurate results than the MRIO framework and we therefore apply the domestic technology assumption when estimating upstream emissions of those products. We establish a column vector s, which includes ones on the position of those products and zeros elsewhere.

In order to assign the upstream emissions of imported products to final use products we apply a single-region input–output model based on the detailed IO table for the Czech economy, which is available for imported products ($\boldsymbol{Z_{imp}}$) and for products of domestic origin ($\boldsymbol{Z_{dom}}$). The technology coefficient matrix ($\boldsymbol{A_{dom\&dta}}$) is calculated as:

$$\boldsymbol{A_{dom\,\&\,dta}} = (\boldsymbol{Z_{dom}} + \widehat{s} * \boldsymbol{Z_{imp}}) * (\widehat{q - m})^{-1} \tag{2}$$

where q is the total supply of products (including imports) and m is a vector of total imports (for intermediate consumption and final demand, this notation is kept as in the Eurostat manual (Eurostat, 2008)).

The upstream emissions of the imported products for which we use the MRIO information ($\boldsymbol{F_{impMR}}$) are calculated as:

$$\boldsymbol{F_{impMR}} = \boldsymbol{F_{imp}} * (\widehat{1 - s}) \tag{3}$$

where 1 denotes a column vector of ones. This sets the emissions of imported products to be estimated through DTA to zero.

Upstream emissions of imported products are then allocated to the users of those products, utilizing the sales structures of the IO table for imported products as:

$$\boldsymbol{F_{impsect}} = \boldsymbol{F_{impMR}} * (\widehat{m})^{-1} * \boldsymbol{Z_{imp}} \tag{4}$$

where m is a vector of total imports. Note that we can use the total vector of imports because the upstream emissions of imported products for which we use DTA are set to zero in the $\boldsymbol{F_{impMR}}$ matrix in Eq. (3).

Some part of imported products is used directly as final demand by households. The upstream emissions of those products are calculated as:

$$\boldsymbol{F_{impyhh}} = \boldsymbol{F_{impMR}} * (\widehat{m})^{-1} * (\widehat{y}_{hhimp}) \tag{5}$$

where y_{hhimp} is the vector of household final demand from imported products. (Again, we do not have to exclude the DTA imported products because the respective emissions are set to zero in the $\boldsymbol{F_{impMR}}$ matrix in Eq. (3).)

Upstream emissions of imported products used in the intermediate consumption are assigned to household consumption using the Leontief approach as:

$$\boldsymbol{F_{impsect2hh}} = \boldsymbol{D_{impsect}} * (\boldsymbol{I} - \boldsymbol{A_{dom\,\&\,dta}})^{-1} * (\widehat{y}_{hhdom\,\&\,dta}) \tag{6}$$

where

$$\boldsymbol{D_{impsect}} = \boldsymbol{F_{impsect}} * (\widehat{q - m})^{-1} \tag{7}$$

$$y_{hhdom\,\&\,dta} = y_{hhdom} + \widehat{s} * y_{hhimp} \tag{8}$$

and y_{hhdom} is the household final demand from domestic products.

Total upstream emissions of household consumption from imports estimated by MRIO ($\boldsymbol{F_{imphh}}$) are calculated as:

$$\boldsymbol{F_{imphh}} = \boldsymbol{F_{impyhh}} + \boldsymbol{F_{impsect2hh}} \tag{9}$$

Upstream emissions of household consumption from the domestic territory and from imported products for which we apply the DTA are estimated as:

$$\boldsymbol{F_{domhh}} = \boldsymbol{D_{dom}} * (\boldsymbol{I} - \boldsymbol{A_{dom\,\&\,dta}})^{-1} * \mathrm{diag}(\widehat{\boldsymbol{y}}_{hhdom\,\&\,dta}) \tag{10}$$

[7] Note that we use $\boldsymbol{F}$ for absolute emissions (irrespective whether direct or upstream) and $\boldsymbol{D}$ for emission intensities (irrespective whether direct or upstream) in order to limit the number of letters. The distinction between direct and upstream is always clearly stated in the text.

where

$$\boldsymbol{D_{dom}} = \boldsymbol{F_{namea}} * (\widehat{q-m})^{-1} \tag{11}$$

Note that while $\boldsymbol{F_{imphh}}$, $\boldsymbol{F_{domhh}}$, $\boldsymbol{F_{impyhh}}$, $\boldsymbol{F_{impsect2hh}}$, $\boldsymbol{F_{impsect}}$, $\boldsymbol{F_{impMR}}$, $\boldsymbol{F_{imp}}$, and $\boldsymbol{F_{impreg}}$ contain upstream emissions, $\boldsymbol{F_{namea}}$ contains only direct emissions of Czech economic sectors. Similarly, $\boldsymbol{D_{dom}}$ contains direct emission intensities of Czech economic sectors, while $\boldsymbol{D_{impsect}}$ contains upstream emission intensities.

The total upstream emissions of household consumption ($\boldsymbol{F_{hhupstream}}$) are then calculated as:

$$\boldsymbol{F_{hhupstream}} = \boldsymbol{F_{imphh}} + \boldsymbol{F_{domhh}} \tag{12}$$

The emission factors $\boldsymbol{D_{hhupstream}}$ to convert household consumption of products in basic prices into upstream emissions are calculated as:

$$\boldsymbol{D_{hhupstreamh}} = \boldsymbol{F_{hhupstream}} * (\widehat{y}_{hh})^{-1} \tag{13}$$

where y_{hh} is a vector of total household consumption (from domestic and imported products).

4. Parallel calculation of embodied emission intensities with MR EE-IOA based solely on EXIOBASE 2

In parallel with the hybrid input–output method, we calculate emission intensities with pure MR EE-IOA using solely EXIOBASE 2. The resulting values were used as a substitution in a few cases where a particular product group is purely imported (e.g. *rice*), not present in such detail in CZ-IOT (e.g. *milk*) or where local values were not regarded as plausible (e.g. *bricks and tiles*).

5. Combination of the embodied emissions from the hybrid input–output method and pure MR EE-IOA

We combine the values of emission intensities from the hybrid input–output method (from step 3) and pure MR EE-IOA (from step 4) to the common resolution of 232 product groups retaining the detail of both 184 product groups of the local CZ-IOT and 200 product groups of the multiregional EXIOBASE (see Supporting information for particular values).

6. Setting up detailed household expenditures

We derive the data on household expenditures from the Czech Consumer Expenditure Survey of 2010 (CZSO, 2011a). It includes data from 2930 households in the resolution of 1682 expenditure items (in Czech Koruna purchasers' prices) in a very detailed COICOP classification for a particular period of the year (typically 2 months) and a complete annual survey of 211 items for these households. Items in finer resolution are used as the ratio for the disaggregation in the case in which sub-items belong to a different product group or have different direct emission intensities. In total, we extract more than 400 applicable items.

7. Allocation of household expenditures to product groups

The CES expenditure items are mapped to 232 product groups. If the CES items could not be mapped one-to-one, where available, the ratio of the respective production technologies to produce the given item is used to allocate the CES expenditures into several product groups. For example, in the case of electricity products, expenditures were allocated according to the contributions of coal, nuclear and hydro power plants to generate electricity. Where official information is not available, an educated guess is used instead.

8. Conversion of the expenditures from purchasers' prices to basic prices

We convert the values (from step 7) from purchasers' prices of the CES to the basic prices[8] of CZ-IOT and EXIOBASE 2 using the data on margins and taxes from the Czech use table (CZSO, 2012) (see Appendix A).

9. Price conversion of imported product groups of 2010 into 2007 prices

To link up CES household expenditures to the EXIOBASE 2, we convert the household expenditures from 2010 to 2007 prices using the product specific Consumer Price Index for imports (CZSO, 2011b) and the 2007 average exchange rate for euro (CNB, 2015).

10. Calculation of individual emissions of eleven pollutants

The obtained set of embodied emission intensities (from step 5) multiplied by expenditures (from step 9) gives us the final values (in kg or g) of all eleven gases for individual households in 232 product groups.

2.3. Total Household Emissions

Using the above calculations, for each household, we derive the values of eleven emissions distributed in 232 product groups, of which 124 are applicable for household consumption. For presentation purposes, we merge direct and indirect emissions together into three environmental impact categories: climate change, acidification and smog formation of CO_{2eq}, SO_{2eq} and C_2H_{2eq}, respectively, utilizing characterization factors provided by Goedkoop (2009). We aggregate the resulting product groups into six consumption groups and sum the emission to get the average for the aggregate and for each decile.

We report the average values of the total emissions for the aggregate (i.e. the entire sample of Czech households) and then for each decile, defined by total yearly expenditures per household member when each household in the CES is weighted to reflect the general Czech population.

We redesigned the twelve main COICOP categories into six consumption groups so that they are logically coherent, significant in terms of their emissions, and still retain sufficient comparability with other studies using original COICOP (Kerkhof et al., 2009b; Weber and Matthews, 2008). As a consequence, this new grouping results in more levelled emission intensities within one group than those of the original COICOP categories. Specifically, the COICOP categories food, alcohol and restaurants form the first consumption group "food". "Transportation" includes expenditures on all modes of public transport, vehicle purchases and fuel plus an estimated portion of recreation expenses attributable to transport. It also includes emissions attributable to transport margins of freight transport. "Goods" covers all varieties of material goods, tobacco, and pharmaceuticals, while "services" consists of all COICOP categories related to communications, health, education, culture, recreation (excluding transport) and other services including auto repair. The COICOP housing category is split into non-energy related expanses categorized as "housing", and energy related expanses defined as "heating", and "electricity". Heating includes expenditures on all fuels used for heating of dwellings or hot water, and the portion of electricity used for heating. This portion of electricity is re-assigned based on average differences in electricity consumption in households with and without electric heating appliances, such as boilers or electric stoves. Expenditures to buy, rent or build a dwelling fall under housing, but this consumption group is purposely excluded from the analysis, since the purchase of a dwelling is considered to be a capital investment.

[8] Only a few papers on EE-IOA mention this issue (Peters and Hertwich, 2006; Steen-Olsen et al., 2016; Wiedmann et al., 2005), and none have provided a detailed description of this procedure.

2.4. Association Between Total Expenditures and Emissions

As Weber and Matthews (2008) point out, household expenditures explain more variation in emissions than income. Total expenditures also ought to be a better proxy than current income for permanent income[9] (Mudgal, 2006) and they might be therefore less sensitive to occasional or temporary situations resulting in lower income, such as illness, maternity leave, or temporary unemployment. To better reflect the relative wealth of a household, we consider the household size and rely on annual expenditures per household member in all further analyses. Following the permanent income hypothesis, we use total expenditures per household member that include also expenditures on housing when elasticity for total emissions is estimated. [10]

We statistically estimate the association between emissions and total expenditures. As with Kerkhof et al. (2009a), Roca and Serrano (2007), and Weber and Matthews (2008), we assume the reduced form of the function $E_j = a \cdot X^{\eta}$ and the double-log model:

$$\ln E_{ij} = \eta \bullet \ln X_i + \varepsilon_i \tag{14}$$

where E_j describes total emissions for jth consumption group (or the consumption aggregate), X is always total household expenditures per household member, the subscript i indicates household, and η is the coefficient to be estimated. Estimating the double-log model implies that η can be directly interpreted as the mean expenditure elasticity.[11]

3. Results

3.1. Emissions Attributable to Average Household

On average, the total direct and indirect emissions per household member and year[12] are 7754 kg CO_{2eq} of greenhouse gases, 22.3 kg SO_{2eq} of acidification gases and 5.66 kg C_2H_{2eq} of smog formation gases for 2010.

Nevertheless, households are not equally responsible for the total emissions attributable to their consumption; 50% of "the poorest households" hold 34.3% of all expenditures and they are responsible for 33.3%, 31.0%, and 31.3% of emissions, respectively. Households in the bottom decile spent 4.5% of all expenditures and are responsible for 4.1%, 3.9%, and 3.8% of emissions contributing to climate change, acidification, and smog formation, respectively. The top decile spends 20.0% of expenditures and is responsible for 19.6%, 24.3%, and 21.8% of emissions, respectively.

Across the four indicators, emissions of $SO_{2eq.}$ are distributed least equally, whereas household expenditures are distributed most evenly (Fig. 1). Expenditures follow similar distribution as emissions of CO_{2eq}, as do SO_{2eq} with C_2H_{2eq}. The Gini coefficient is 0.231 for expenditures and 0.240, 0.273, and 0.287 for greenhouse gases (CO_{2eq}), smog formation (C_2H_{2eq}), and acidification (SO_{2eq}), respectively.

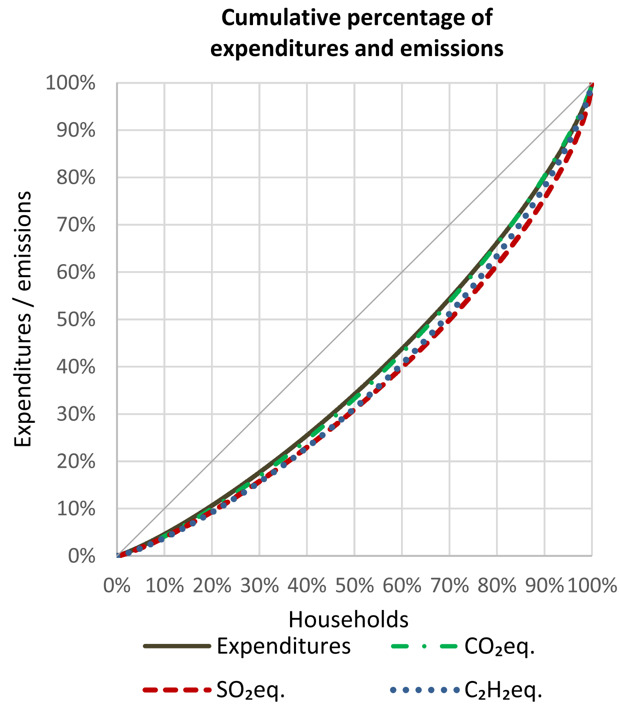

Fig. 1. Distribution of expenditures, CO_{2eq}, SO_{2eq}, and C_2H_{2eq} emissions (N = 2930). The Gini coefficients are 0.231, 0.240, 0.287, and 0.273, respectively.

The mean annual total household expenditure is 240,803 CZK (that is equivalent to 9521 EUR) and the corresponding mean per household member is 120,688 CZK (4772 EUR) and standard deviation of 56,923 CZK (2251 EUR). The weighted mean of expenditures is 109,003 CZK (4310 EUR) per household member and year, with standard deviation of 52,115 CZK (2061 EUR).[13] Their respective average emission intensities are 1.86 kg CO_{2eq}, 5.36 g of SO_{2eq}, and 1.33 g of C_2H_{2eq} for each EUR of household expenditures in 2010.[14]

Contributions from six consumption groups[15] to the total consumption expenditures and their respective emission intensities are reported in Table 1 and depicted graphically in Fig. 2. In expenditures, food and goods prevail, while electricity and heating together are responsible only for 14%.

There are two consumption groups, heating and electricity, dominating in emissions that make more than 62% of the total climate change and 53% of acidification emissions. Emissions attributable to transportation and heating prevail with a 56% share in smog formation. Consumption of services and goods always contributes the least share, 5–8% and 8–12%, respectively, although households spend on them 17% and 27%.

For whole consumption, higher variance in the intensities across households is for SO_{2eq}, while intensity of CO_{2eq} emissions has the lowest variance. Expenditures on electricity and heating are three times more intensive than transportation and about one order of magnitude more emission intensive than the other four groups. Transportation is, however, the most intensive for emissions contributing to smog

[9] As noted by Gibson and Bonggeun (2013), using short-run expenditures from household surveys as a proxy of permanent income may create attenuated estimates of its impact on economic outcomes. Since CES records expenditures over whole year for most of the items except food, the measurement error due to misreporting is small.

[10] Most similar studies have reported the indicators per person and we follow this approach. Nonetheless, in our calculations we have used three different definitions of household expenditures: per family member (reported in this paper), equalized expenditures per consumer unit, following the OECD definition, and total expenditures per household. We have found that the emission intensities and expenditure elasticities are very close across all three definitions of household expenditures. These results are available on request to the authors.

[11] The expenditure elasticity, $\eta = \frac{X}{E}\frac{\partial E}{\partial X}$, measures the percentage change in the quantity of environmental impact, E, resulting from a 1% increase in the annual equivalent household expenditures, X. The calculation is based on the individual data of 2930 households.

[12] Since the CES records a frequency weight with which each household is represented in the general Czech population, we derive and report the results as the weighted average per household member rather than the simple arithmetic mean per person. Consequently, because this weighting is linked to households rather than to individuals, the results cannot be interpreted as averages per capita of the whole population.

[13] Nominal values in Czech crowns are expressed in EUR using the mean 2010 exchange rate 25.29 CZK per 1 EUR.

[14] Unless it is stated otherwise, all results exclude expenditures on and emissions from housing.

[15] Expenditures to buy, rent or build housing are excluded from the analysis, since the purchase of a dwelling is considered to be a capital investment (Eurostat, 2008, pp. 155). See Section 2.3 for further information. If spending on housing were included, the intensities are 1.60 kg CO_{2eq}, 4.63 g SO_{2eq}, and 1.19 g C_2H_{2eq}, respectively, per EUR of total expenditures, including but not counting emissions from housing.

Table 1
Average annual expenditure per household member and emission intensities for six consumption groups with standard deviation in parentheses, the Czech Republic, 2010.

	Expenditure (EUR)	Climate change (kg CO_{2eq}/EUR)	Acidification (g SO_{2eq}/EUR)	Smog formation (g C_2H_{2eq}/EUR)
Food	1330 (520)	0.78 (0.05)	4.09 (0.51)	0.72 (0.05)
Electricity	231 (130)	6.81 (0.00)	14.34 (0.00)	1.63 (0.00)
Heating	428 (290)	7.31 (2.48)	21.41 (46.97)	3.44 (3.10)
Transport	443 (971)	2.35 (0.66)	5.41 (2.19)	4.27 (2.55)
Goods	1166 (831)	0.51 (0.10)	1.58 (0.34)	0.57 (0.08)
Services	712 (487)	0.60 (0.15)	1.49 (0.37)	0.66 (0.22)
Total expenditure/average intensities	4310 (2061)	1.86 (0.55)	5.36 (2.97)	1.33 (0.47)

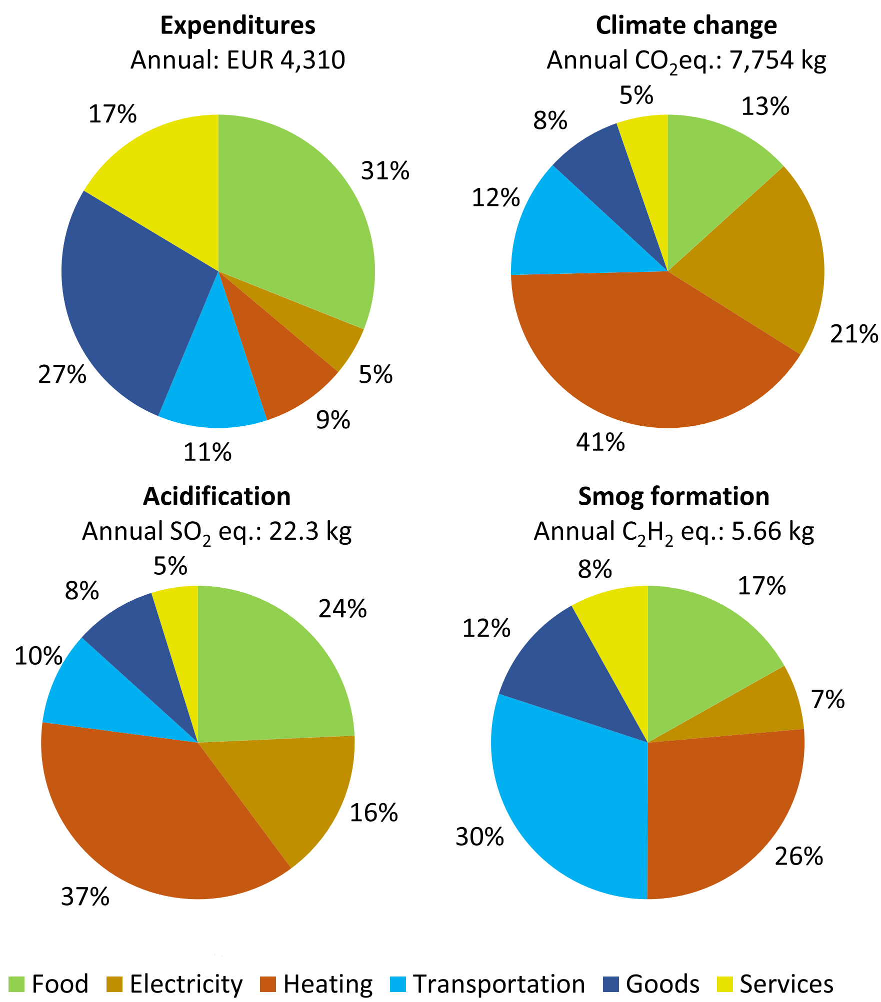

Fig. 2. Expenditures and environmental impacts by six consumption groups, the Czech Republic, 2010. Stated values present the means per household member and year.

formation. We find the largest variance, indicating larger heterogeneity on consumed goods, in the emission intensities for heating and transportation. On the other hand, electricity represents a homogenous item that implies zero variance. From the remaining consumption groups, the emission intensity of food has relatively small variance across households for each of the three emission indicators.

The total volume of emissions in each consumption category is given by the combination of two factors: the expenditures spent on each item of goods that make up the sub-aggregate, and the emission intensity of each consumption item. The aggregate emissions can be also derived as a scalar product of six group-expenditures and their intensity counterparts (Table 1). Even average emission intensities vary greatly across the six consumption groups, for example, one euro spent on heat is responsible for 7.38 kg of CO_{2eq}, while one euro spent on food is responsible for only 0.77 kg of CO_{2eq}. Fig. 2 displays the relative contributions of an average household member from each consumption category to the total emissions.

In the case of climate change related emissions, more than half stem from heating and electricity. The extent of expenditures on food and transportation means that their total emissions contribute significantly despite their comparatively low emission intensities. As for transportation, more than half of the emissions are attributable to individual transportation and the rest go towards passenger or freight transportation on buses, trains and airplanes. Approximately half of the GHG emissions from food originate from N_2O and CH_4. The vast majority of N_2O comes from agriculture from fertilized soils and livestock manure. Almost 40% of CH_4 comes from the population of ruminant animals. The rest of CH_4 is divided mostly between heating, electricity and the

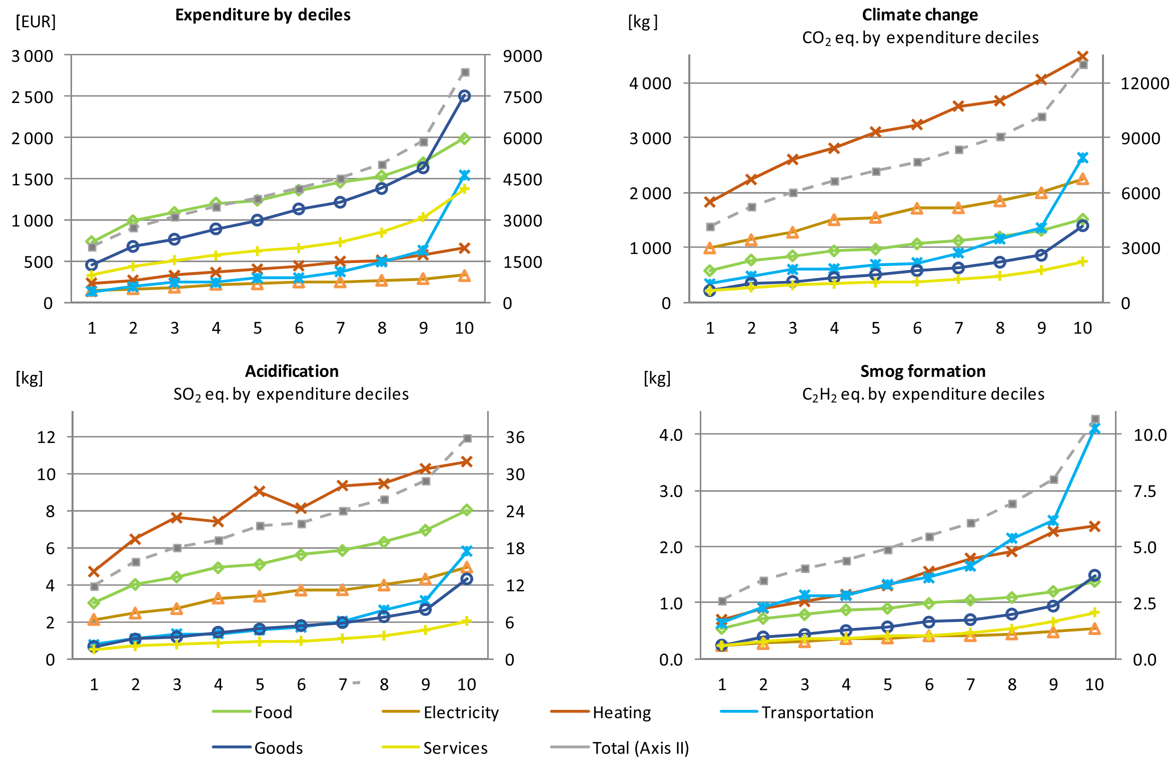

Fig. 3. Expenditures and environmental impact categories by deciles for 6 consumption groups and for total expenditures. Annual average values per household member and year, the Czech Republic, 2010.

remaining consumption groups, with its origin in coal mining. When comparing these results with the Netherlands, the United Kingdom, Sweden and Norway (Kerkhof et al., 2009a), Czech households have smaller emissions per household member in all consumption groups with the exception of heating and electricity.[16] The smaller emissions are mainly the consequence of smaller expenditures, reflecting lower GDP per capita. On the other hand, much of the electricity in the Czech Republic is produced in CO_2 intensive coal power plants, which account for 57% of total electricity production, and widespread district heating utilizes coal as a fuel in 56% of heat production. Other factors that might influence both energy consumption and emissions are climatic differences and different thermal insulation rates. In sum, these factors make heating and electricity stand out above transportation and goods, which are, unlike in other countries, less important in the case of the Czech Republic.

For acidification, heating, food and electricity are dominant sources. About half of the acidification effect is attributable to SO_2. This is traceable not only to the electricity and heating, where about one half of SO_2 emissions originate, but also (indirectly) to all other consumption groups, probably stemming from electricity generated from coal, which is used in the majority of industrial processes. Two main sources of ammonia (NH_3) emissions are the population of ruminant animals and application of agricultural fertilizers. The sources of NO_x are mainly diesel propelled freight, public transportation vehicles and agricultural machinery. Higher values of acidification emissions from electricity and heat generation have their origin in SO_2 stemming from significant coal usage, which may contrast with countries where other sources of energy prevail, like natural gas in the Netherlands (Kerkhof et al., 2009b) and in the United Kingdom or hydropower in Sweden and Norway.

Smog formation is prevailingly induced by NMVOC emissions, whereas the CO contribution is almost negligible. Fig. 2 shows that the C_2H_{2eq} emissions originate largely from transportation (30%) and heating (26%). This is in contrast to other countries, for instance, transportation constitutes more than 50% of NMVOC emissions in the Netherlands (Kerkhof et al., 2009b). The different trend in the Czech Republic may be the outcome of several reasons: the usage of more emission intensive coal for heating compared to natural gas, about 30% fewer passenger-kilometers driven by the Czechs (Eurostat, 2015a), and slightly lower share of petrol cars in the Czech Republic (Eurostat, 2015b). Kerkhof et al. underestimate emissions associated with imported products, probably since they apply domestic technology assumption and so, consequently, the use of relatively clean Dutch technology is assumed instead of the actual technologies in the regions of origin of the imported products.

3.2. Emissions Attributable to Households by Expenditure Decile

Emissions attributable to households vary considerably across expenditure deciles; per household member, they span from the first to the tenth decile from 4157 to 13,012 kg of CO_{2eq} for greenhouse gases, from 11.8 to 35.8 kg of SO_{2eq} for acidification, and from 2.6 to 10.7 kg of C_2H_{2eq} for smog formation (see Fig. 3). The magnitude is growing gradually from the first to tenth decile. This trend is common for all three emission indicators as well as expenditures. The sharpest increase is in the last tenth decile, because it is amplified with long-term investments in expensive items such as cars in transportation or furnishings in goods. Such purchases usually help to qualify the household into the 10th expenditure decile and therefore, the composition of this decile is different from the others. However, it is not likely that these

[16] Heating and electricity in our study are compared to the COICOP housing category that includes expenditures on heating and electricity, in other studies. Our comparison with the studies by Kerkhof et al. (2009a) and Kerkhof et al. (2009b) is included to put our research in perspective with results from other European countries. Nevertheless, a thorough comparison would require a separate analysis. Also note that the source data for the Czech Republic and the four comparison countries were all taken in different years, Netherlands (2000), Norway (1997–1999), Sweden (2002–2005), and the UK (1998–1999). This may in turn influence the household emissions to a certain degree, above all because of the fluctuation in economy or differences in weather in heating season.

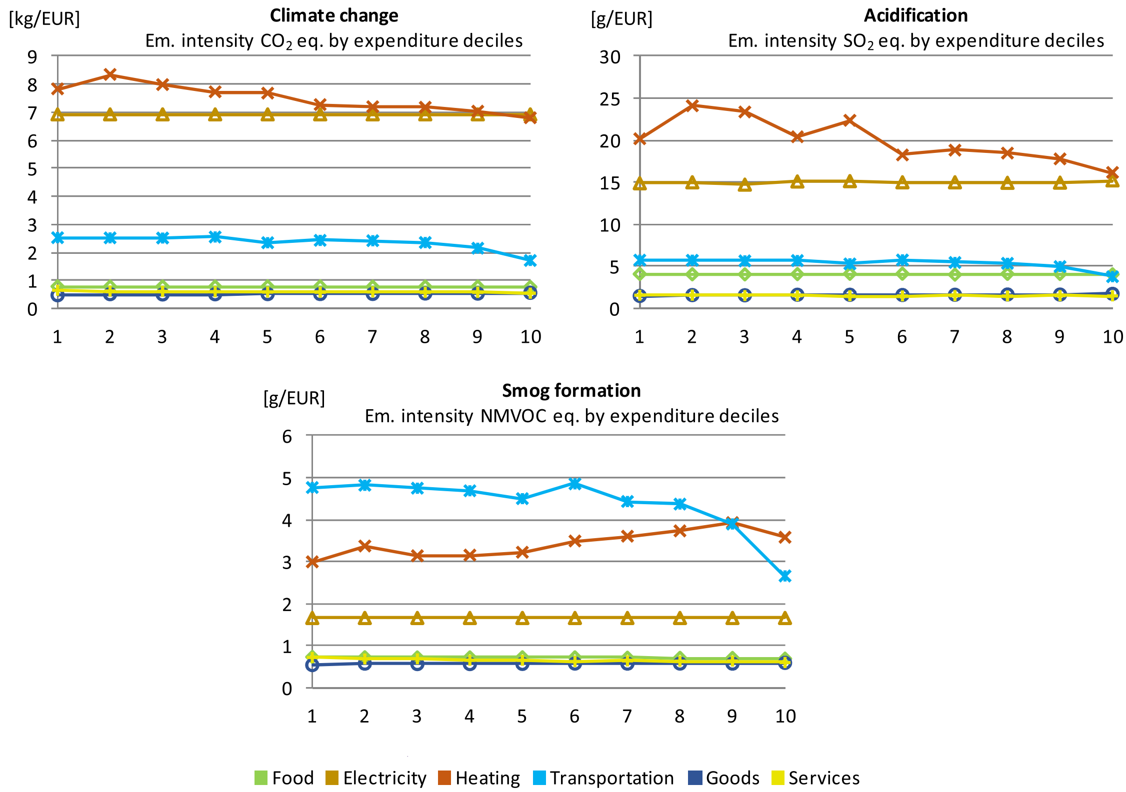

Fig. 4. Emission intensities for three environmental impact categories by deciles. Average values per household member, the Czech Republic, 2010.

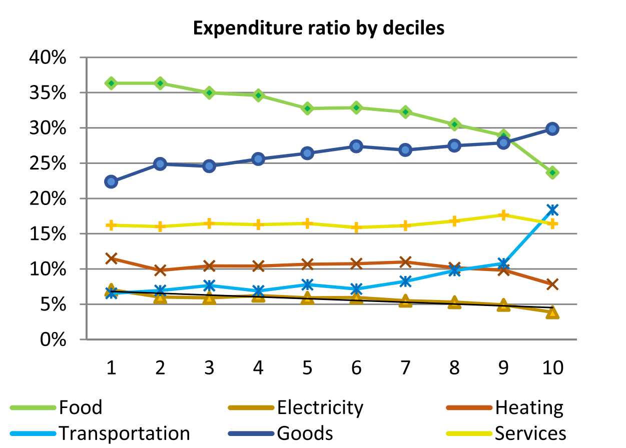

Fig. 5. Expenditure shares of six consumption groups by deciles. Based on annual average values of total expenditures per household member, the Czech Republic, 2010.

purchases are made by these particular households every year.

Further, we examine three factors that may influence these results for each decile; the emission intensities, expenditure shares, and absolute expenditures.

The first factor, emission intensities are relatively constant across all ten deciles for each consumption group with the exception of heating and transportation (Fig. 4). The decline in emission intensity of heating across deciles is the result of largely coal powered emission intensive district heating in the apartment buildings of less wealthy households compared to the family houses of wealthier households which are more often heated by natural gas. Emission intensity for transportation descends in the highest expenditure deciles mainly due to lump sum on car purchases, which compares to other more intensive transportation products, such as diesel or petrol.

Despite the fact that the goods and services, that households buy and consume, are very heterogeneous and may vary to a large extent even across one production group, the averaged emission intensity of the whole group is almost same for these consumption groups for all deciles.

The next factor influencing the magnitude of the emissions is the composition of household expenditures (Fig. 5). At least in the Czech

Table 2
The mean of expenditure elasticity (η), 95% confidence interval (CI) and coefficient of determination (R^2) for all three environmental impacts in each of the consumption groups. Expenditures include expenses on housing and are expressed per household member and year, the Czech Republic, 2010.

	Climate change				Acidification				Smog formation			
	ε	CI		R^2	ε	CI		R^2	ε	CI		R^2
Food	0.68	±	0.023	0.54	0.70	±	0.024	0.52	0.66	±	0.023	0.53
Electricity	0.53	±	0.041	0.18	0.56	±	0.043	0.18	0.53	±	0.041	0.19
Heating	0.72	±	0.072	0.12	0.69	±	0.102	0.08	0.66	±	0.080	0.06
Transportation	1.17	±	0.102	0.15	1.20	±	0.104	0.10	1.11	±	0.121	0.15
Goods	1.20	±	0.042	0.52	1.21	±	0.042	0.54	1.18	±	0.039	0.52
Services	0.88	±	0.038	0.42	0.97	±	0.042	0.40	0.88	±	0.039	0.41
Total	0.81	±	0.026	0.55	0.80	±	0.033	0.52	0.86	±	0.030	0.44

case, the proportion of expenditures on goods and transportation increases at the expense of food as household expenditures increase. Also, electricity share descends slightly which could be caused, besides electricity consumption itself, by cheaper tariffs for higher electricity consumption on one hand and fixed costs for electrical fuses on the other. The rapid increase, about 7%, in the transportation share in the last decile is caused by lump sum expenditures on cars.

The last factor, household expenditures, grows steadily across the deciles on all six consumption groups (Fig. 5). This turns out to be the overwhelmingly decisive factor for the emission differences between the deciles.

3.3. Expenditure Elasticity of Emissions

Next, we investigate econometrically the association between household expenditures per person and their environmental impact. These estimates of expenditure elasticities for the consumption aggregate and the six consumption groups for each of the three environmental impact indicators are displayed in Table 2. Since we are interested in the association with total expenditures, as a measure of permanent wealth, the total expenditures including expenses on housing are used for calculations.

All estimates of the elasticities displayed in Table 2 are statistically significant at the significance level $\alpha = 0.01$. The total expenditure elasticity is 0.81 for GHGs, 0.80 for acidification emissions, and 0.86 for emissions contributing to smog formation. Table 2 also reports the elasticity estimates for the six consumption groups; all are in a range of 0.53 to 1.21. Emissions are most sensitive to expenditures within the consumption group transportation and goods, with the elasticity estimates around 1.2. The values over one imply that emissions attributable to these consumption groups increase more than proportionally with expenditures and they partly indicate the more luxurious character of these consumption groups and partly reflect one-time purchases of less emission intensive furnishings and cars. Emissions in all three impact categories attributable to electricity are the least sensitive to expenditures, with elasticities around 0.55. Slightly larger elasticity is found for food and heating, between 0.66 and 0.72, again for each of the three environmental problems. In contrast to goods and transportation, food, heating and electricity describe consumption satisfying more basic needs.

Our estimates of the total expenditure elasticities (Table 2) are comparable to the estimates derived by Kerkhof et al. (2009b) in their Dutch study. For GHGs Kerkhof et al.'s estimate is 0.84, which lies within the Czech confidence interval. The slightly lower value of the Czech estimate for acidification, 0.80, compared to the estimate for the Netherlands, 0.96, is a probable consequence of more frequent usage of district heating, predominantly generated from coal, in lower deciles and the shift to natural gas heating in family houses that are more often occupied by “richer households”. This is the same effect, mentioned already above, which causes the decline in emission intensity of heating. Finally, the lower Czech elasticity estimate for smog formation, compared to 1.42 for the Netherlands is likely a consequence of the fact that the NMVOC emissions stem almost exclusively from transport in the Netherlands, whereas in the Czech Republic the other less elastic consumption groups, such as heating, significantly influence the elasticity as well.

The highest coefficients of determination, indicating the best way the model explains variability in data, were recorded for food and goods. Since the prevailing determining factor of household emissions is absolute values of the expenditure, the high coefficient of determination for these two consumption groups might be the consequence of more noticeable prices and a consequent deliberate reduction in spending. This is in contrast to utilities where consumers usually do not track the information continuously. Also in the case of food and goods, households most often get the amount proportional to what they pay for. On the contrary, electricity is sold with two-part tariff and heating may include a portion of common costs in block of flats. Emissions from heat consumption are also highly influenced by other non-wealth related factors, such as type of fuel used, thermal insulation and type and size of a dwelling. The transportation expenditures are obvious and easily controllable, but their high variance of expenditure elasticity suggests that these expenditures are also dependent on other factors, such as personal choice or situation, rather than a deliberate spending limitation derived from one's own spending budget.

4. Discussion

Microdata based on household surveys usually underestimate expenditures and hence the total aggregates are given smaller values than those recorded in the final household demand (Kok et al., 2006; Weber and Matthews, 2008). In order to validate our approach based on CES, we compare average expenditures and emissions based on CES with expenditures and emissions based on the final demand of households from CZ-IOT, keeping the same emission coefficients. For expenditures, we find that the CES average represents overall 71.9% of expenditures recorded in the final demand of CZ-IOT. As could be expected, the expenditure values in CES are closest to CZ-IOT final demand values for electricity (87.1%) and heating (85.9%), which are quite homogenous and usually yearly or monthly paid consumption groups, whereas they display the greatest deviation for services (61.3%) which consist of variety of heterogeneous items. Consequently, we find that that emission values based on the CES data encompass 85.2% of GHGs, 87.9% of emissions causing acidification, and 81.1% emissions contributing to smog formation, all derived from the final demand.

As in any other input–output modelling, where several databases are linked, there are a number of limitations, some having already been pointed out, for instance the homogeneity assumption with respect to product goods or industries (Kerkhof et al., 2009b; Peters and Hertwich, 2006; Reinders et al., 2003; Steen-Olsen et al., 2016; Weber and Matthews, 2008).

Neither CES nor IOT was designed primarily for environmental analyses. When linking the two databases with different classifications, the product homogeneity assumption and heterogeneity of environmental impacts attributable to various goods pose a problem. Secondly, the items purchased by households do not match other dominant products in the product group which they belong to, with regard to their material, expected price and production process, e.g. when a home lamp belongs to a product group otherwise consisting of electric motors and electronic components.

Regarding the microdata on household expenditures, household surveys usually underestimate the consumption of certain goods, e.g. alcohol, and under-represent particular segments of households, the wealthier households in particular. Moreover, households' revenues from the sale of used goods are usually not recorded by items in CES, thus their embodied emissions cannot be possibly deducted as negative emissions. Additionally, households might benefit from various types of fully subsidized consumption, above all the provision of a company car or mobile phone for personal purposes. This consumption is not reported in CES. Lastly, there is a general problem of how to account for the emissions attributable to the purchase of durable goods, since the embodied emissions should be ideally spread over the whole lifetime of the purchased good, but the required information for such re-distribution is not a part of CES databases.

Unless a unit price is applied, the association between expenditures and quantity is more complex. In reality, there are several cases in which expenditures are not proportional to consumed quantities and hence to its emissions. First, some services are paid as a lump sum, e.g. a waste disposal service. Second, more complex pricing schemes are applied for most utilities (electricity and heating). Third, some services are greatly subsidized or provided for free without any fixed measured cost, e.g. public education and health care, resulting in negligible or zero expenditures. Last, the emission intensity factor derived for an

'average product' of a certain product group does not serve as a good measure for emissions associated with expenditures on luxury and branded goods or labor intensive services. Consequently, emissions attributable to households that purchase relatively more of these goods and services are most likely overestimated.

Special attention should be paid to the expenditures of households to buy a house or flat which are, unlike any other expenditure, a part of gross fixed capital formation in IOT. Above that, they are considerably underreported in CES and, at the same time, buying or building of dwelling is a long-term investment not reflected annually. In order to apply a consistent approach across households, we exclude emissions from the rental of a house or flat from our analysis. If we chose to include them with the current method, it would make up 3–5% of the total emissions. Environmental accounting for these expenditures remains for further research.

5. Conclusions

Within this paper we combine the SR and MR EE-IOA to utilize the strengths of both methods in order to gain more accurate results of almost 3000 individual households' total, direct and indirect, emissions for a total of 232 product groups for eleven different substances. The eleven emissions are aggregated into three environmental impact indicators: climate change, acidification and smog formation. The average values per household member and year 2010 are 7754 kg CO_{2eq}, 22.3 kg SO_{2eq}, and 5.66 kg C_2H_{2eq}.

Our results for the Czech Republic show that expenditures on food and goods predominate for total household expenditures, whereas for climate change it is heating and electricity, for acidification it is heating and food, and for smog formation it is traffic and heating. The apparent prevalence of heating and electricity is caused by the domestic energy mix. The two dominating consumption groups make up more than 50% of the total emissions aggregated into each of the three environmental impacts.

The emissions attributable to household consumption are not distributed evenly. Emissions per household member increase along expenditure deciles. Emission distribution is even slightly more unequal than for expenditures. From closer examination of the relationship between expenditures and emissions, we find that larger emissions are a clear consequence of the overall increased expenditures and hence, the consumption of wealthier households and the differences in the composition of the consumption do not influence this trend much.

The expenditure elasticities are all positive and significant, in a range of 0.53 to 1.21; however, the coefficients of determination reveal different strengths in this association across the six consumption groups.

The emission intensity of expenditures on different consumption groups varies considerably. The emission intensity of heating and electricity is about tenfold larger than that of goods and services (with respect to climate change and acidification) and food (with respect to climate change only) (see Fig. 4). Each euro spent on personal transportation generates about one-third of the emissions related to climate change and acidification compared to heating, and half that of electricity generation. In the case of smog formation, transportation, followed by heating are the most emission intensive consumption groups. Overall, we found that the variation in the emission intensities is much smaller across the ten deciles than across the six consumption groups.

Emissions grow proportionally with income with expenditure elasticities between 0.80 and 0.86 on the aggregate level. And since the total annual expenditures are growing considerably across deciles (from around 2500 EUR in the two bottom deciles to more than 6000 and 9000 EUR in the two top deciles), "richer households" are responsible for considerably more emissions than households from the lowest deciles. These differences are even more pronounced for goods and transportation, as expenditure elasticities for these two consumption groups exceed one.

An effective policy should therefore target consumption groups with the highest emission intensities, heating and electricity to combat climate change and acidification, and transportation and heating to reduce emissions contributing to smog. Secondly, policy may consider the fact that "richer households" are responsible for more emissions. As an example, a non-linear energy price schedule that uses increasing block rates is the policy that may reduce energy consumptions and hence emissions of "richer households" and simultaneously it minimizes possible adverse social effects on "poorer households". The carbon intensity of heating and electricity is similar; however spending one euro on heating generates more acidification and smog formation gases than one euro spent on electricity (see Table 1). Policy measures to introduce the usage of renewables and installation of energy savings particularly in residential heating should therefore be supported.[17] Additionally, we believe that our results contribute to the design of effective environmental policies, since the importance of indirect emissions may have not been recognized so far by many policy makers, or, especially, by the general public.

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Appendix A. Conversion From Final Prices of Expenditures to Basic Prices

Only a few papers on EE-IOA mention the transformation of purchaser prices to the basic prices of CES (Wiedmann et al., 2005; Peters and Hertwich, 2006; Steen-Olsen et al., 2016) and none of them describe their calculation. On that account, we cover this topic within this paper in more detail.

The tables of CZ-IOT and EXIOBASE 2 are recorded in basic prices, in contrast to CES, which is collected in purchases' prices. For that reason, household expenditures are transformed so that taxes and subsidies are deducted, and transport and trade margins are deducted and redistributed to the product groups which they belong to. In general, this can be formulated mathematically as:

$$\mathbf{E_b} = \mathbf{E_p}\,(\widehat{\mathbf{c^t}} + \mathbf{C^m}) \tag{A1}$$

where $\mathbf{E_p}$ and $\mathbf{E_b}$ stand for a matrix of household expenditures in purchasers' and basic prices respectively. Diagonal matrix $\widehat{\mathbf{c^t}}$ subtracts the taxes and margins from each product group i. Its vector entries are calculated as follows:

$$\{c_i^t\} = \left\{\frac{p_i}{p_i + r_i + t_i}\right\} \tag{A2}$$

[17] The example of such support is the Ministry of the Environment's Green Savings Programme administered by the State Environmental Fund of the Czech Republic since 2009.

where p_i is domestic production plus imports, r_i are margins and t_i are taxes plus subsidies for each product group i in absolute values obtained from the use table (CZSO, 2012). In cases where the production and import total is $p_i = 0$ then also $\{c_i^t\} = 0$.

To redistribute margins proportionally to their providing product groups j, the $\mathbf{C^m}$ matrix with c_{ij}^m entries is used:

$$\{c_{ij}^m\} = \left\{\frac{r_i}{p_i + r_i}\frac{r_j}{\sum_j r_j}\right\} \tag{A3}$$

for all product groups i. Consequently, $\{c_{ij}^m\} = 0$ for all product groups j, which do not provide margins.

Within this study, the transport surcharge is internalized into railway, land, pipeline, coastal and inland ship transportation. The trade surcharge is internalized in three parts. The margin on motor vehicles is internalized into the vehicle trade product group, all propellant margins to the propellant trade product group and margins on all other products are transferred to the wholesale trade and retail trade product groups.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.02.015.

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